

From ion O⁺ outflow to substorm impact on plasmasheet O⁺ injections fluxes

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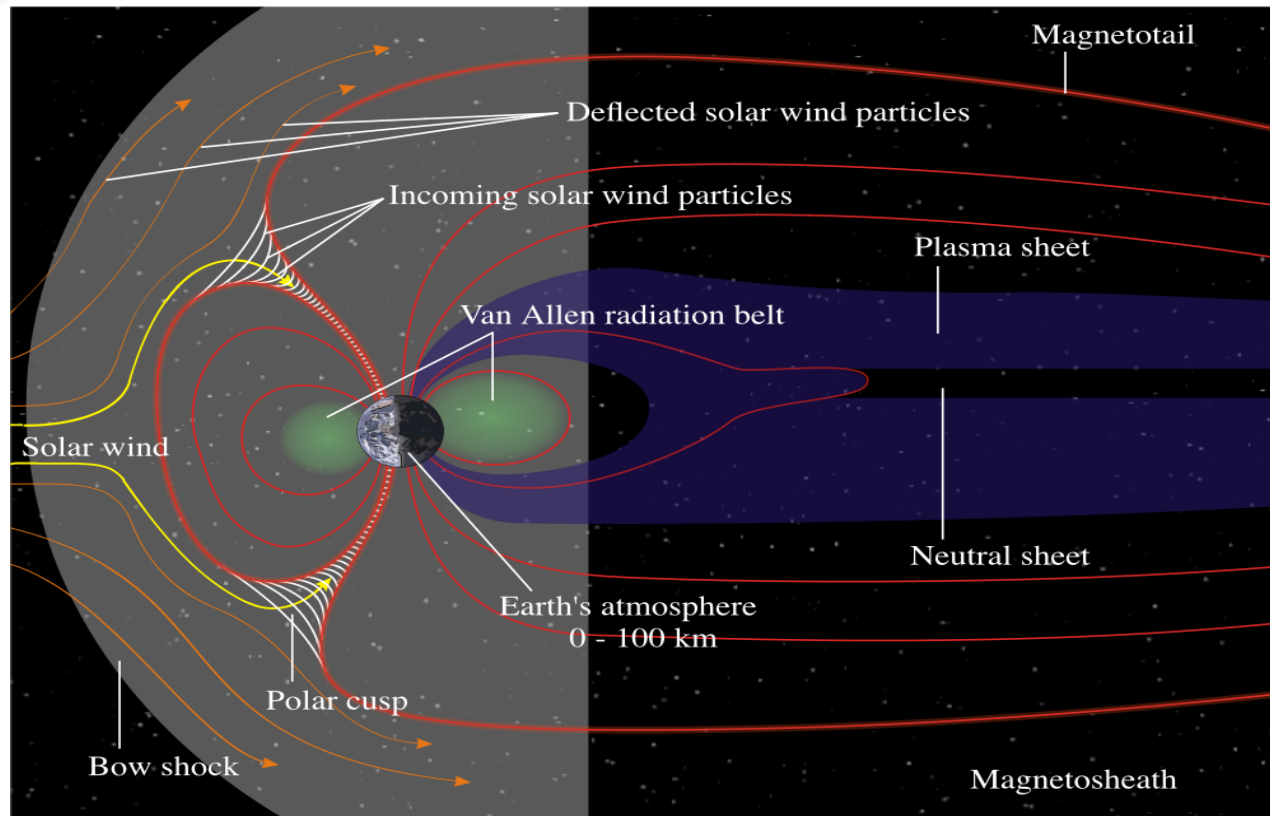
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Outline

- Introduction: the problem investigated
- Numerical modelling tools
- Preliminary results on O⁺ injections to inner magnetosphere

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The magnetosphere and its populations

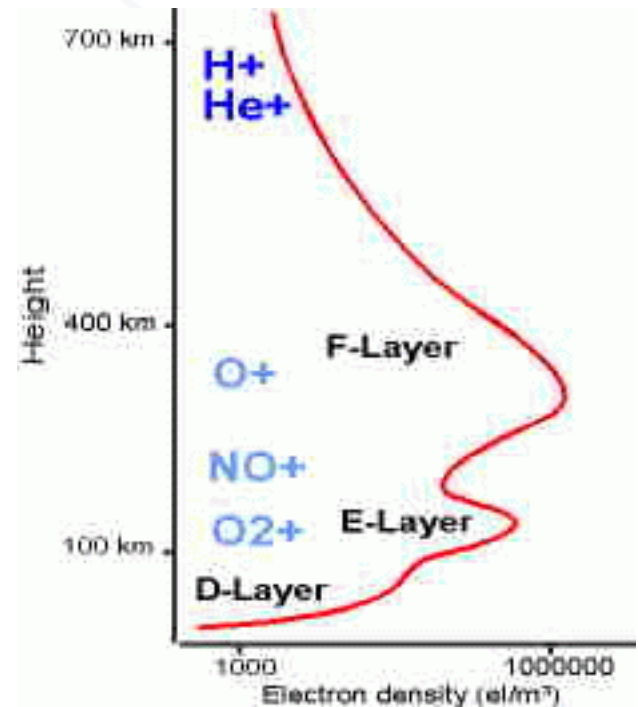


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Ionospheric outflow:

Basic information

- Extends roughly from 60km to 1000km
- Outflow occurs usually at high latitudes
- Ions that escape the gravitational pull are mostly in the F-layer \rightarrow H^+ , He^+ and O^+
- Greater ionization on the dayside due to UV radiation. Thus, it generates a greater outflow on the cusp region.
- Outflow is also affected by geomagnetic storms.



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Where does the ionospheric O⁺ go?

What do we know?

- Ionospheric outflow is an important component of the plasma in the plasmasheet. (André and Yau, 1997)
- O⁺ density and abundance in the nightside at geosynchronous orbit increase significantly with both K_p and F_{10.7}. He⁺ increases with F_{10.7}, but not significantly with K_p. (Kistler and Mouikis, 2016)
- Outflow fluxes from the cusp are also greater during active times.
- O⁺ is the dominant species in the ring current during the main phase of geomagnetic storms. (Daglis, 1997)

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What is the effect of ionospheric ions in the inner magnetosphere?

Several parameters influence ion fluxes at GEO

- What is the impact of geomagnetic storms and substorms on geosynchronous fluxes and ion composition at the nightside?
- Is the path of the different species coming out of the ionosphere the same?
- Can we determine what parameters (SW dynamic pressure, SWBz, location and intensity of plasmasheet electric field, occurrence of substorms) are most important in evaluating conditions at GEO?

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What is the path of O⁺ from ionosphere to ring current?

The problem and the hypothesis

- How does the O⁺ from the ionosphere gets to the plasmasheet and ring current in the time scales observed?
- Peterson (2009) suggested that rapid reconfiguration of the magnetosphere during strong geomagnetic storms significantly alter the O⁺ transport paths from ionosphere to plasmasheet.
- Mass of O⁺ in the lobes is estimated to be as much as 4300kg.

Geomagnetic Activity	Variable	Reservoir			
		Plasmasheet		Ring Current	
	Solar Activity	Minimum	Maximum	Minimum	Maximum
Quiet times	O ⁺ mass (kg)	1000	4000	50	300
	Source rate (kg/s)	0.2	1.2	0.2	1.2
	O ⁺ mass/source rate (min)	80	60	4	4
Storm times	O ⁺ mass (kg)	27,000	27,000	4,500	4,500
	Source rate (kg/s)	18	110	18	110
	O ⁺ mass/source rate (min)	25	4	4	1

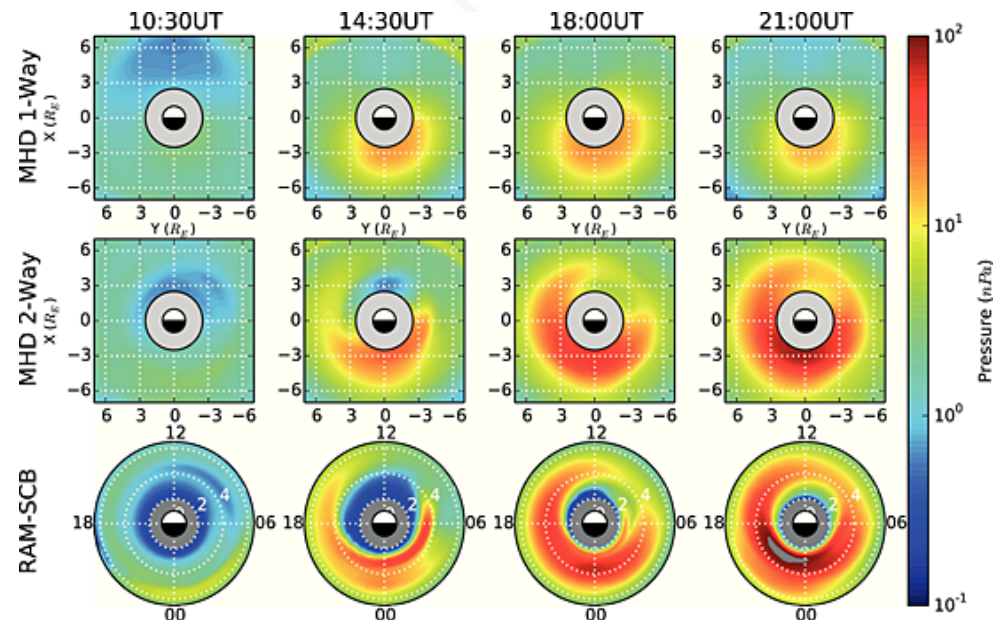
Table 1: Estimated O⁺ reservoir masses, source rates and mass-to-source-rate ratio for various solar and geomagnetic activity conditions (*Peterson et al.*, 2009).

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Why is this problem important?

One of the reasons: improving ring current models

- Our understanding about the ring current comes from modeling studies supported by sparse in-situ observations.
- Plasmasheet is the primary source for the ring current.
- Ring current models make assumptions about the source and composition of their species based on statistical studies.
- The increased energy and mass density from oxygen can boost wave growth and propagation.
- Underestimation of O⁺ makes a great impact.



Equatorial pressure profiles on MHD and ring current simulations.

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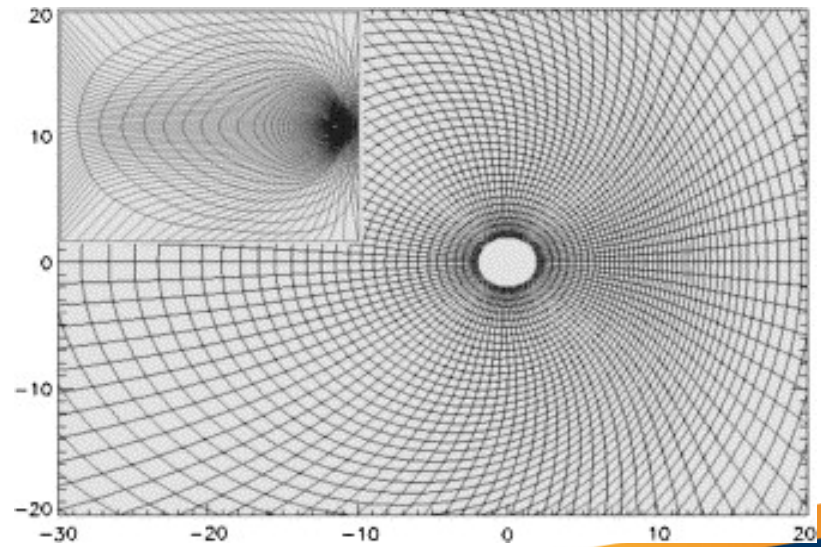
Why use test particle simulations?

- Constant advances in storage and computing power are making simulations cheaper, faster and more accurate.
- Ions from the ionosphere are a low density and high energy population, ideal for test particle approach.
- Look at the global picture.
- Simulate ideal conditions or real storms using the MHD global simulations (LFM).
- Keep track of all parameters of interest.

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LFM – MHD global 3D simulations

- Solar wind parameter as dayside boundary conditions.
- Super alfvenic and super sonic outflow on the nightside.
- Solves MHD equations on a 3D grid.
- Conserves $\nabla \cdot \mathbf{B} = 0$
- Grid adapted to magnetosphere



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Test particle simulation

Uses guiding center and Lorentz equations

- Uses Lorentz equation when necessary

$$\frac{d(\gamma \mathbf{v})}{dt} = \frac{q}{m} \left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} \right)$$

- Mostly uses relativistic guiding center equations (Cary and Brizard, 2009)

$$\begin{aligned} \frac{d\mathbf{X}}{dt} &= \frac{p_{\parallel}}{m\gamma} \frac{\mathbf{B}^*}{B_{\parallel}^*} + \mathbf{E}^* \times \frac{c\hat{b}}{B_{\parallel}^*} \quad \text{with,} \\ \mathbf{E}^* &= \mathbf{E} - \frac{1}{e} \left(mc^2 \nabla \gamma - p_{\parallel} \frac{\partial \hat{b}}{\partial t} \right) \\ \frac{dp_{\parallel}}{dt} &= e \mathbf{E}^* \cdot \frac{\mathbf{B}^*}{B_{\parallel}^*} \\ \mathbf{B}^* &= \mathbf{B} + \frac{cp_{\parallel}}{e} \nabla \times \hat{b} \end{aligned}$$

*New addition:
Gravity terms*

- Adaptive time steps:

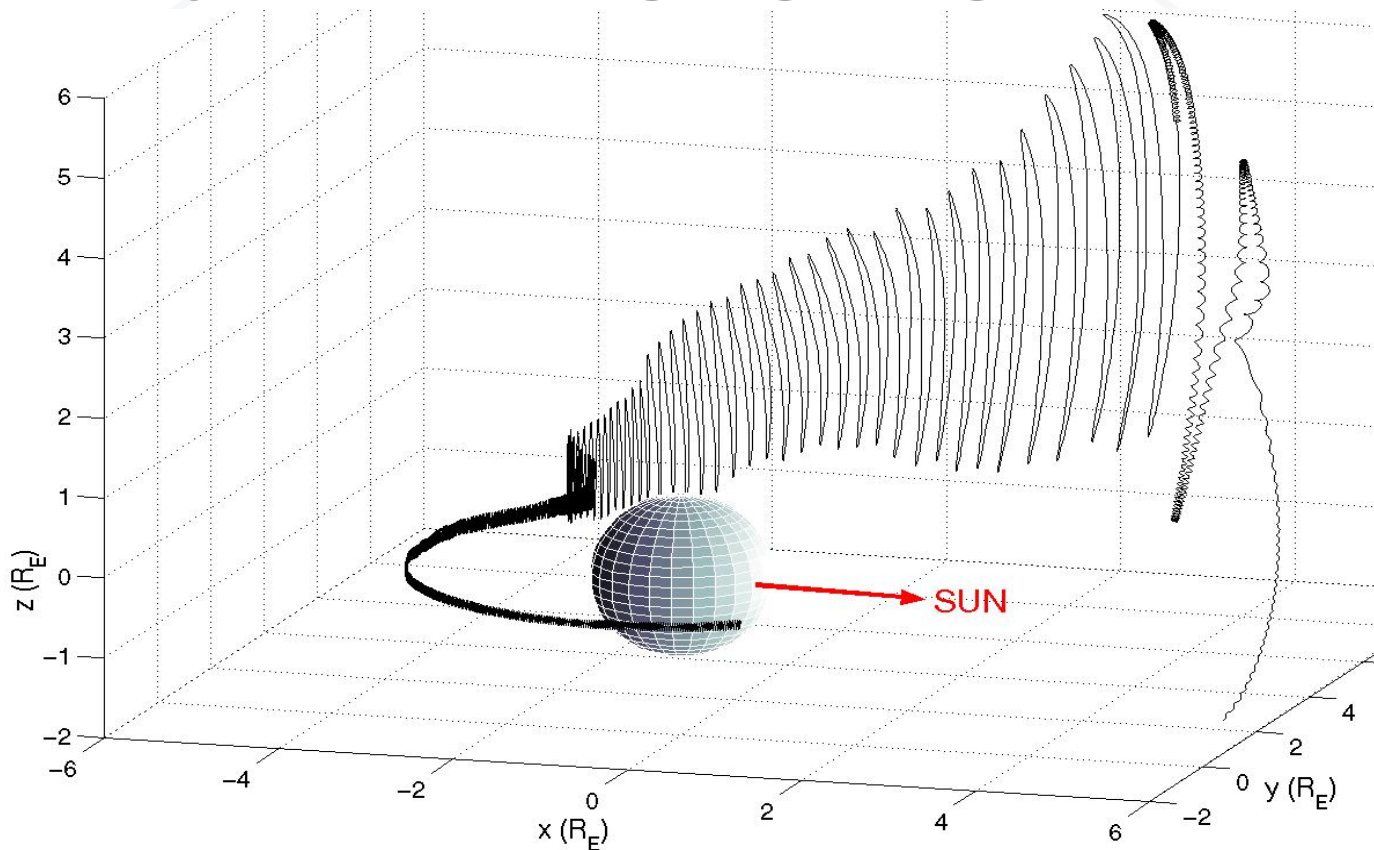
$$\delta t_L = \varepsilon_1 T_g = \varepsilon_1 \frac{2\pi m}{qB}$$

$$\delta t_{GC} = \frac{p}{\max(F_{\nabla B}, F_C, F_E, \dots)}$$

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Test particle simulation

Example of switching to guiding center



Kress et al. 2007

Trapping of solar wind energetic electron in dynamic MHD fields

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Calculating the initial distribution function

Shifted velocity-space Maxwellian:

$$f(\mathbf{v}) = A \cdot \left(\frac{m}{2\pi kT} \right)^{3/2} \cdot \exp \left(-\frac{m(\mathbf{v} - \mathbf{v}_b)^2}{2kT} \right)$$

Assume the beam velocity \mathbf{v}_b is along the ambient field:

$$f(v, \alpha) = A \cdot \left(\frac{m}{2\pi kT} \right)^{3/2} \cdot \exp \left(-\frac{m(v^2 + v_b^2 - 2v_b v \cos \alpha)}{2kT} \right)$$

From the observations we have the characteristic energy, E_0 , and flux of upflowing ions, J_b . We assume the parallel component of the characteristic energy is the beam energy and the perpendicular component as the temperature:

$$v_b = \sqrt{\frac{2E_0}{m}} \cos \alpha \quad kT = E_0 \sin^2 \alpha$$

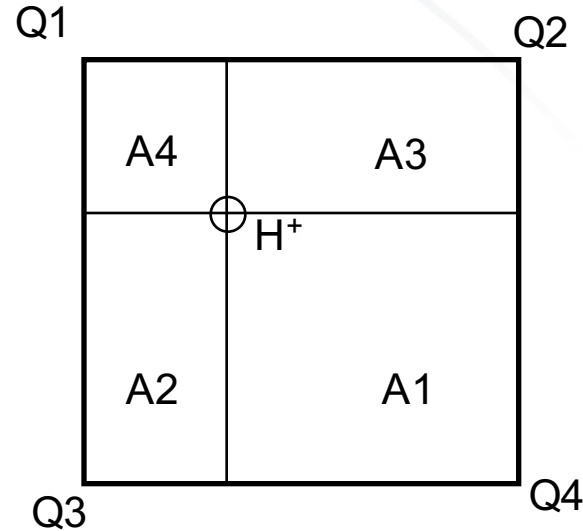
For an isotropic initial distribution, $A=n/p$, where n is estimated from the beam flux and velocity, $n=J_b/v_b$. Then for each particle starting with a velocity v and pitch angle α , we assign an initial f based on the boundary coordinate measurements of E_0 and n via

$$f(\mathbf{v}) = \frac{n}{\pi} \cdot \left(\frac{m}{2\pi E_0 \sin^2 \alpha} \right)^{3/2} \cdot \exp \left[-\frac{mv^2}{2E_0 \sin^2 \alpha} + \left(v \sqrt{\frac{2m}{E_0}} - 1 \right) \cot^2 \alpha \right]$$

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Calculating the distribution function from MHD/testparticle simulations

- Initial phase space density assigned based on LEO sats observations.
- Phase space density of each test particle held constant along trajectory (Liouville's Theorem).
- PSD calculated via weighted average on cartesian grid in equatorial plane.
- Moments calculated to get evolving density and temperatures.



$$f_0 = \frac{j_{obs}}{p^2}$$

$$f_1 = \frac{\sum_i f_{0,i} \frac{A_{1,i}}{A}}{\sum_i \frac{A_{1,i}}{A}}$$

$$n(\mathbf{x}, t) = 4\pi \int_0^\infty \int_0^\infty f(\mathbf{x}, v_\perp, v_\parallel, t) v_\perp dv_\perp dv_\parallel$$

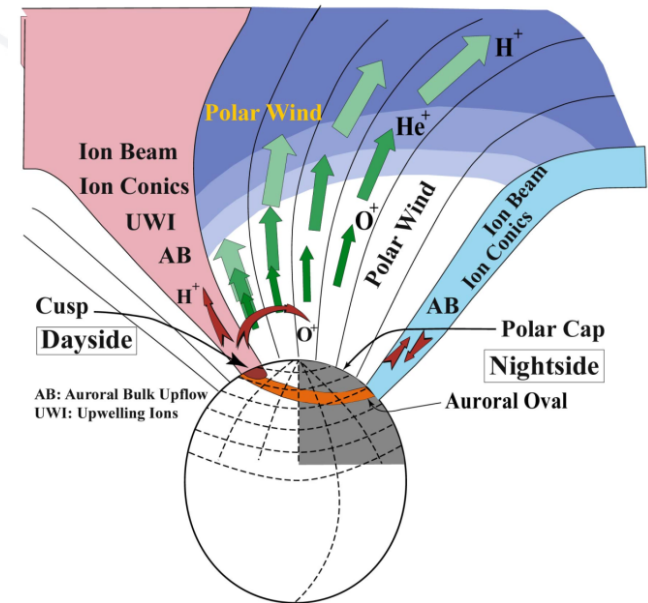
$$T_\perp(\mathbf{x}, t) = \frac{2\pi m}{k_B n} \int_0^\infty \int_0^\infty f_l(\mathbf{x}, v_\perp, v_\parallel, t) v_\perp^3 dv_\perp dv_\parallel$$

$$T_\parallel(\mathbf{x}, t) = \frac{4\pi m}{k_B n} \int_0^\infty \int_0^\infty f_l(\mathbf{x}, v_\perp, v_\parallel, t) v_\parallel^2 v_\perp dv_\perp dv_\parallel$$

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Ion outflow during quiet conditions

We wish to understand the quiet-time transport of O^+ from the ionosphere, and resulting distribution of particles in the plasmasheet and lobes, with the ultimate goal of understanding the impact of these particles on the development of the ring current with the onset of geomagnetic activity.



O⁺ energetics

Thermal: $\sim 1000^\circ \text{K}$ - 700 m/s
Upwelling $\sim 1 \text{ km/s}$ (0.01 eV)
Escape $\sim 11 \text{ km/s}$ (10 eV)
Required to reach 6,000 km
 $\sim 6 \text{ km/s}$ (5 eV)

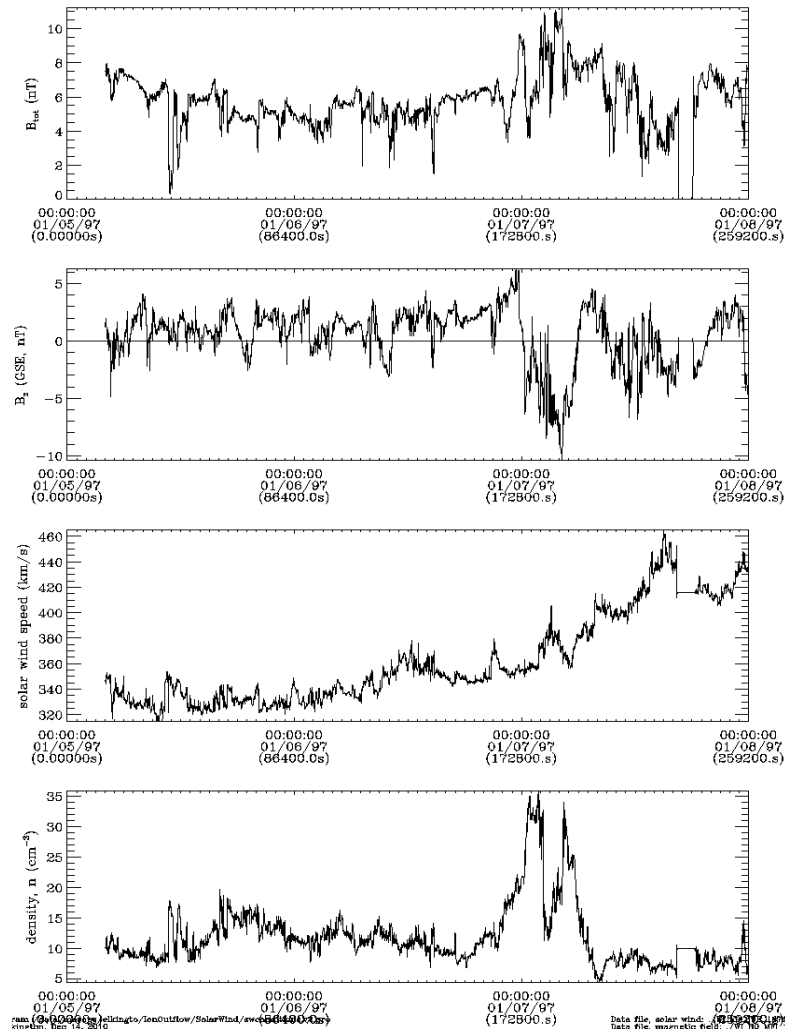
O⁺ Observations

	Energy Range (keV)	Altitude (km)
DE -1	0.01 - 17	<20,000
Polar	0.015 - 33	8,000
Akebono	0-0.070	<9,000
FAST	0.003-12	<4,000

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The January 5-9, 1997 period

Study of ion outflow during a real event

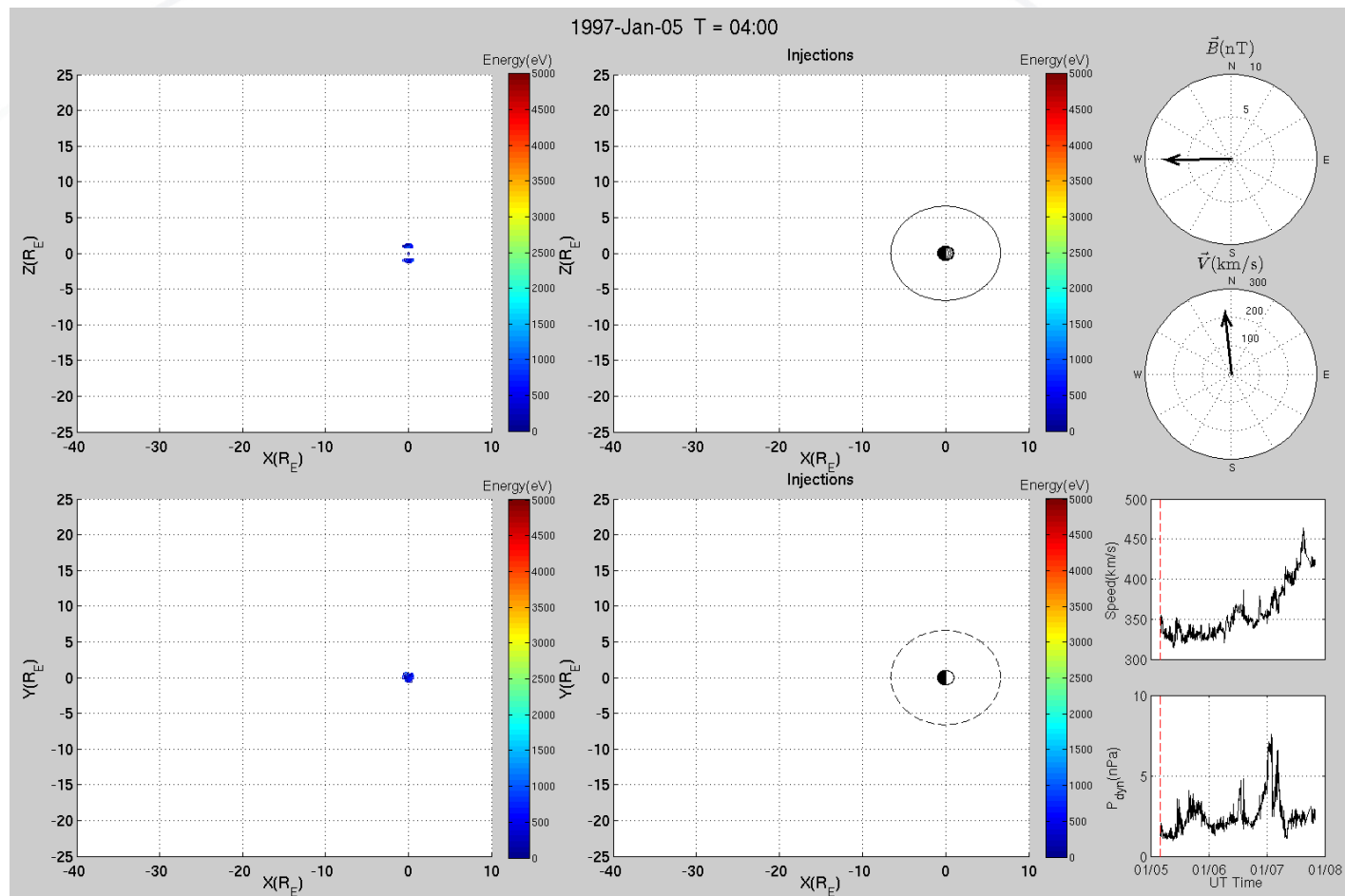


- This was a quiet period prior to the January 1997 magnetic cloud event.
- Injected test particles uniformly in time during the entire period.
- Test particle domain $dx=[-44,12]$, $dy=[-15,15]$, $dz=[-16,26]$
- ~500M test particles @1.1Re from both hemispheres.
- Energy range – 10 eV to 1keV
- Dipole tilt during this period varied between 12 to 33 degrees.

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Preliminary Simulation Results

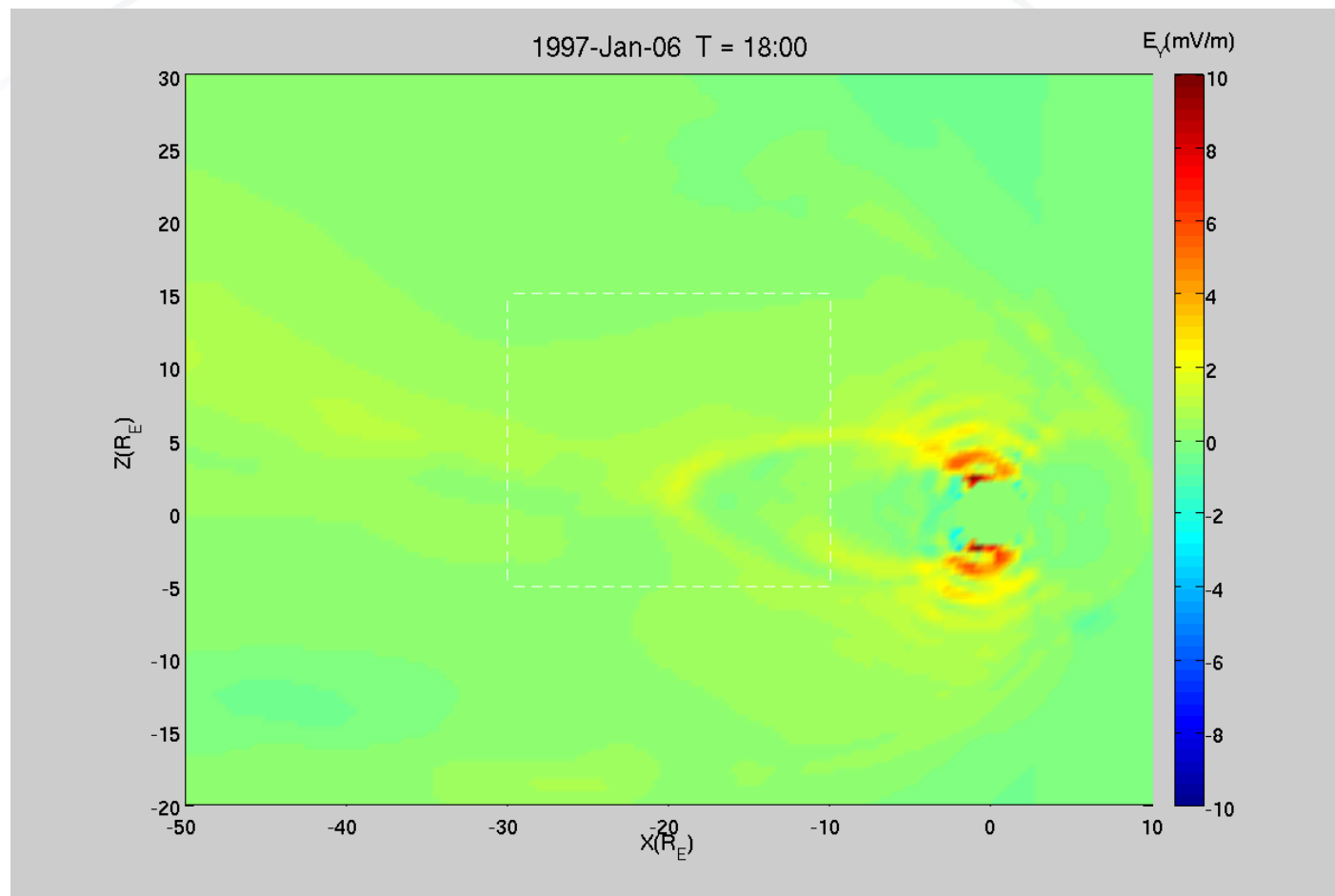
Injection features



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Preliminary Simulation Results

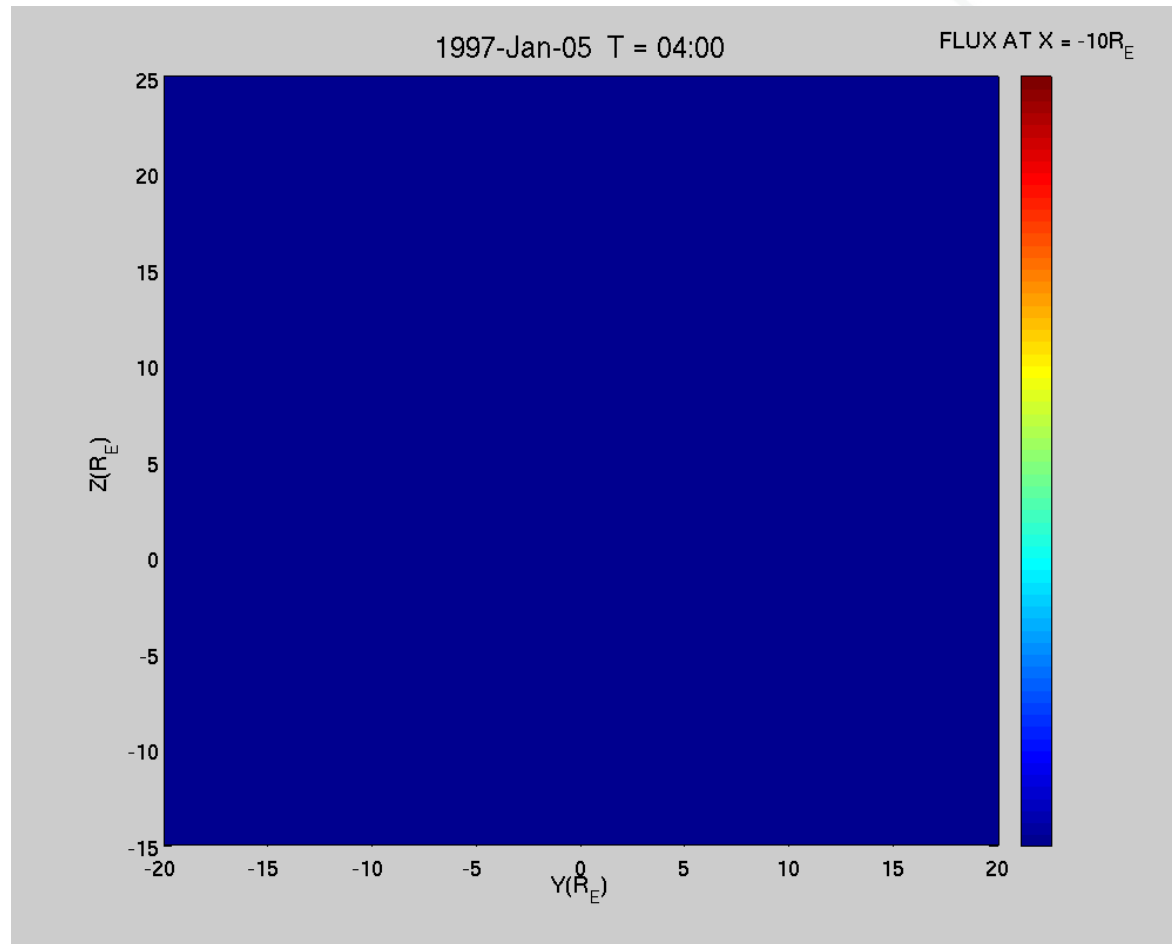
Plasmasheet Ey



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Preliminary Simulation Results

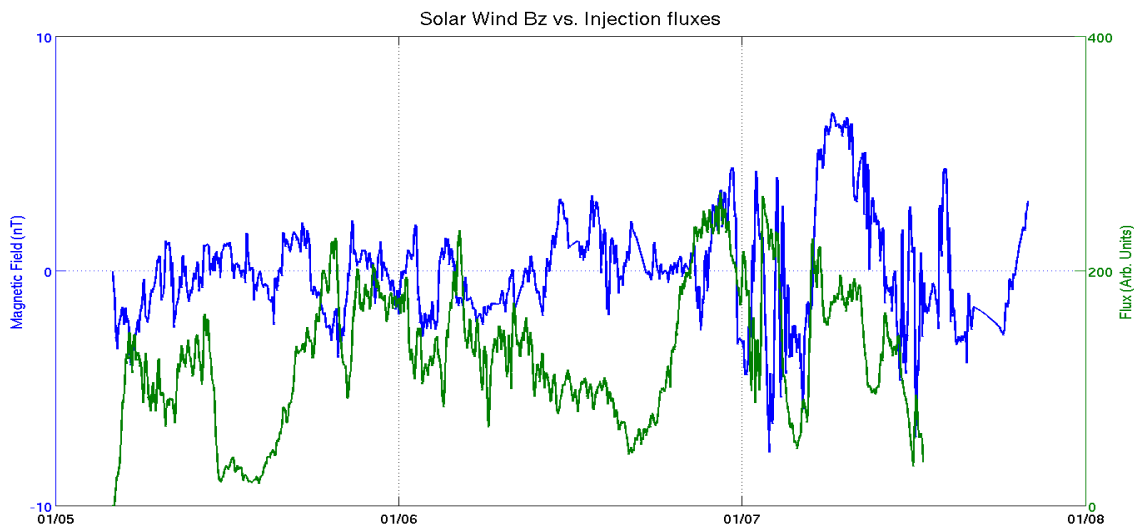
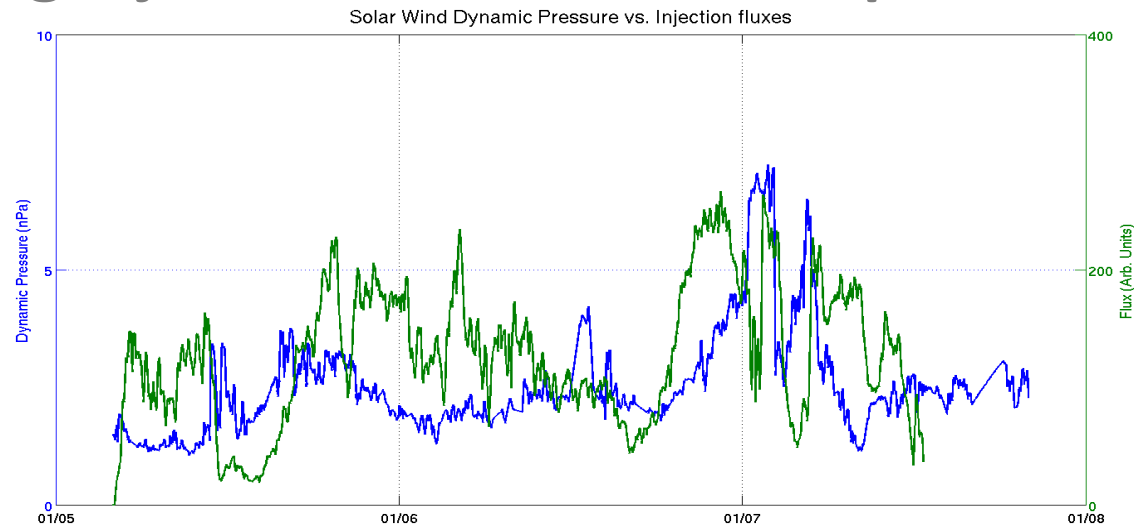
Tail fluxes at $X = -10R_E$



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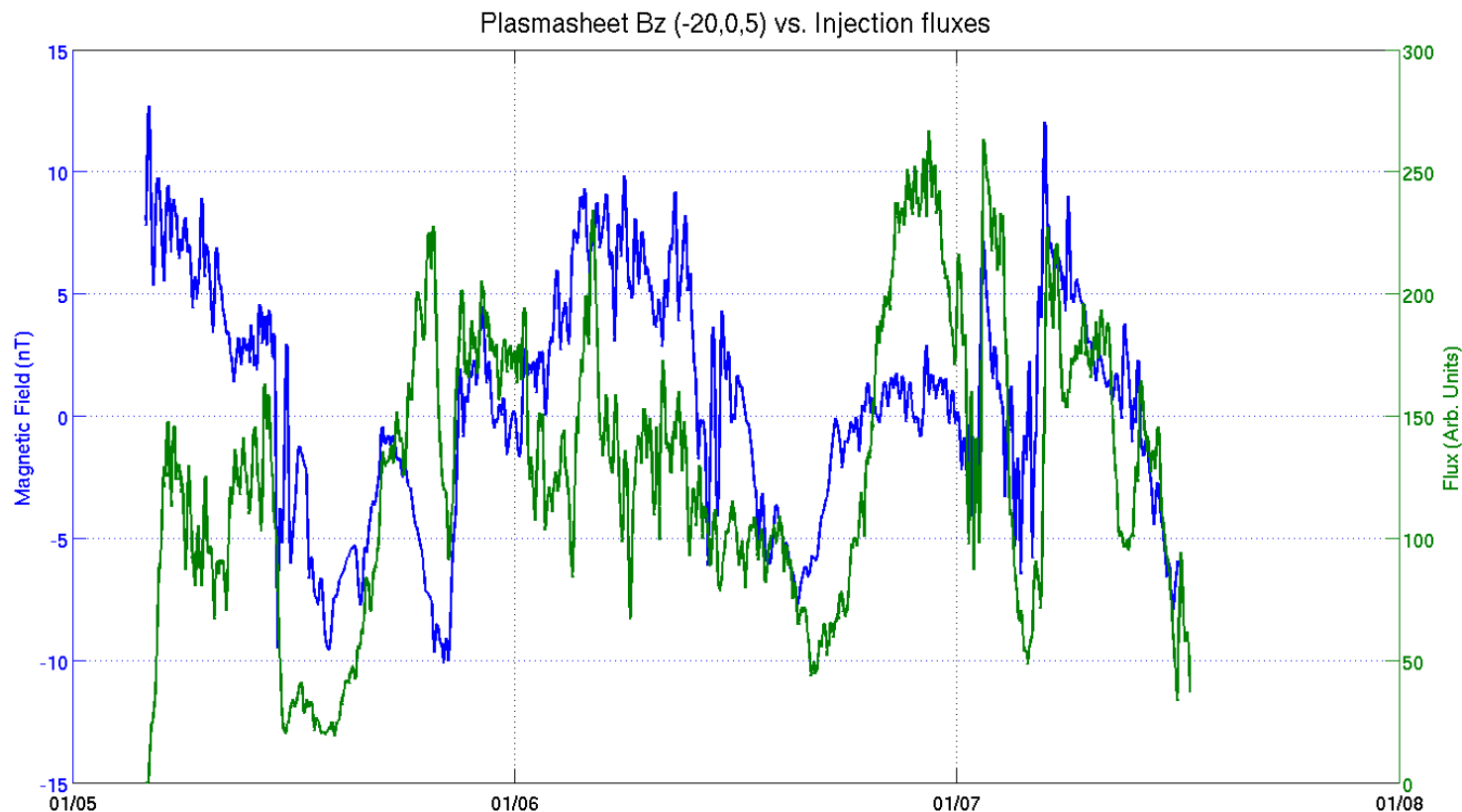
Preliminary Simulation Results

Comparing injection with solar wind parameters



Preliminary Simulation Results

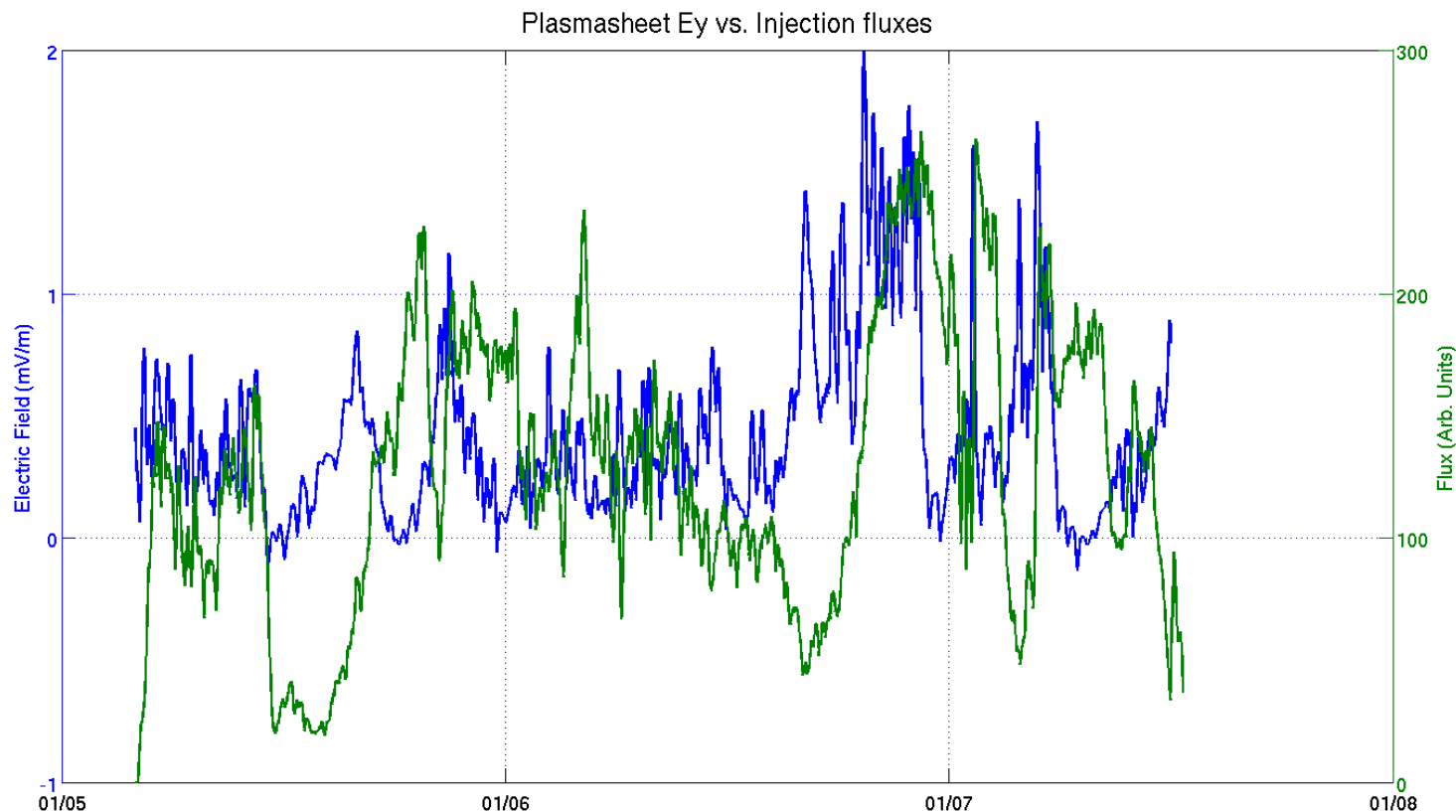
Comparing injection with plasmashield parameters



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Preliminary Simulation Results

Comparing injection with plasmashield parameters



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Summary

- Quantifying ion fluxes at GEO during storm periods and substorms is essential to out ring current models.
- Using test particle simulations of ions starting at the ionosphere and making their way into the ring current can be a useful tool to measure the impact of storms and substorms on geo fluxes and ion composition.
- Preliminary outflow simulation results indicate that there is a correlation between the y-component of the electric field in the plasmasheet region and O⁺ injection fluxes as expected.

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